More Than Cloud: New techniques for characterizing reservoir structure using induced seismicity

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Interest in using microearthquakes for characterizing petroleum and geothermal reservoirs and the region surrounding underground mines has grown considerably over the last several years. A comprehensive understanding of the fracture distribution and hydrogeomechanical processes occurring during operation provides valuable information for reservoir development and optimization of production. Some of this information can be obtained from well logs, but they only provide direct information about conditions near the well. Microseismic (MS) monitoring techniques can be primary methods for obtaining detailed information about reservoirs and fracture systems at locations as far as 1 km from boreholes.

In traditional studies of reservoir seismicity, MS mapping is carried out and images of the locations within the reservoir are used to infer reservoir characteristics. Thus, a key issue with MS mapping is the accuracy of event location. Reliability of locations can be severely compromised by the small number and often poor spatial distribution of sensors recording waveforms from the microearthquakes. This is particularly true in offshore hydrocarbon applications where borehole access is limited. The events are frequently distributed as a "cloud," and we are able to visualize only a blurred image of the seismically active region from this cloud. Information on detailed reservoir structure, fracture orientation, and hydraulic behavior cannot be obtained from application of conventional earthquake location techniques using sparsely distributed networks. In addition, interpretation of MS data has been limited by our overall understanding of processes taking place at the source of the events. Thus, although MS has been demonstrated to provide vital input into petroleum and geothermal characterization and management, it remains an area of frontier research. This article will present some results from an international R&D collaboration known as "MTC—More Than Cloud" that has been addressing these issues.

MTC. In February 1993, researchers in a number of countries joined together to study aspects of microseismic observations that would go beyond simple mapping of clouds of hypocentral locations—hence the name "More Than Cloud." These researchers brought with them different types of observations at widely varying geographical sites and represented industry, government labs, and academic organizations.

Direct collaboration was facilitated when MTC received direct funding from the New Energy and Industrial Development Organization of Japan. The Ministry of Education, Science, Sports, and Culture of Japan provided additional funds for basic academic research.

Progress in five areas will be described in the remainder of this paper:

- Improved estimations of the absolute and relative locations of microseismic events.

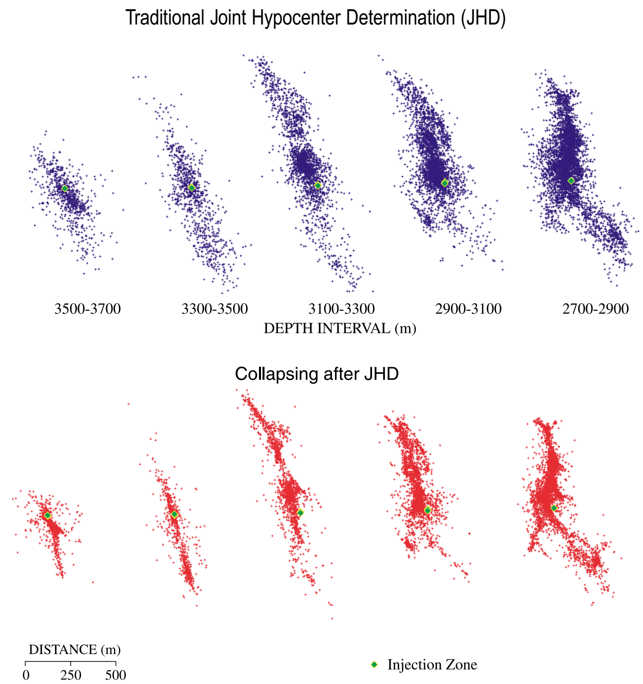


Figure 1. Plan view maps of microearthquakes accompanying a hydraulic injection in France. Maps are shown for events occurring within depth intervals in the stimulated region. The upper set of maps was determined using a Joint Hypocenter Determination approach; the lower set shows the locations after application of the collapsing technique to the upper set of locations. The collapsing process has removed much of the scatter in the original location distribution. Note that the direction of growth of the stimulated region, toward the NW away from the injection zone, shown with a diamond, can be clearly seen in the location set after collapsing.

- Reflection method using microearthquakes and drill-bit signatures as seismic sources for imaging.
- Hypocenter tomography to determine internal velocity structure of the reservoir when few seismic observation stations are available.
- Multicomponent signal processing for phase picking and characterization of sensor reliability.
- Observations and modeling of crack waves guided along the interface of fluid-filled cracks to infer hydraulic characteristics of cracks.

Improved absolute and relative locations of microseismic events: Location maps are the primary information obtained from MS observations. Locations are determined from traveltimes measured on MS waveforms recorded at a number of stations. In hydrofracturing-induced seismicity studies, events

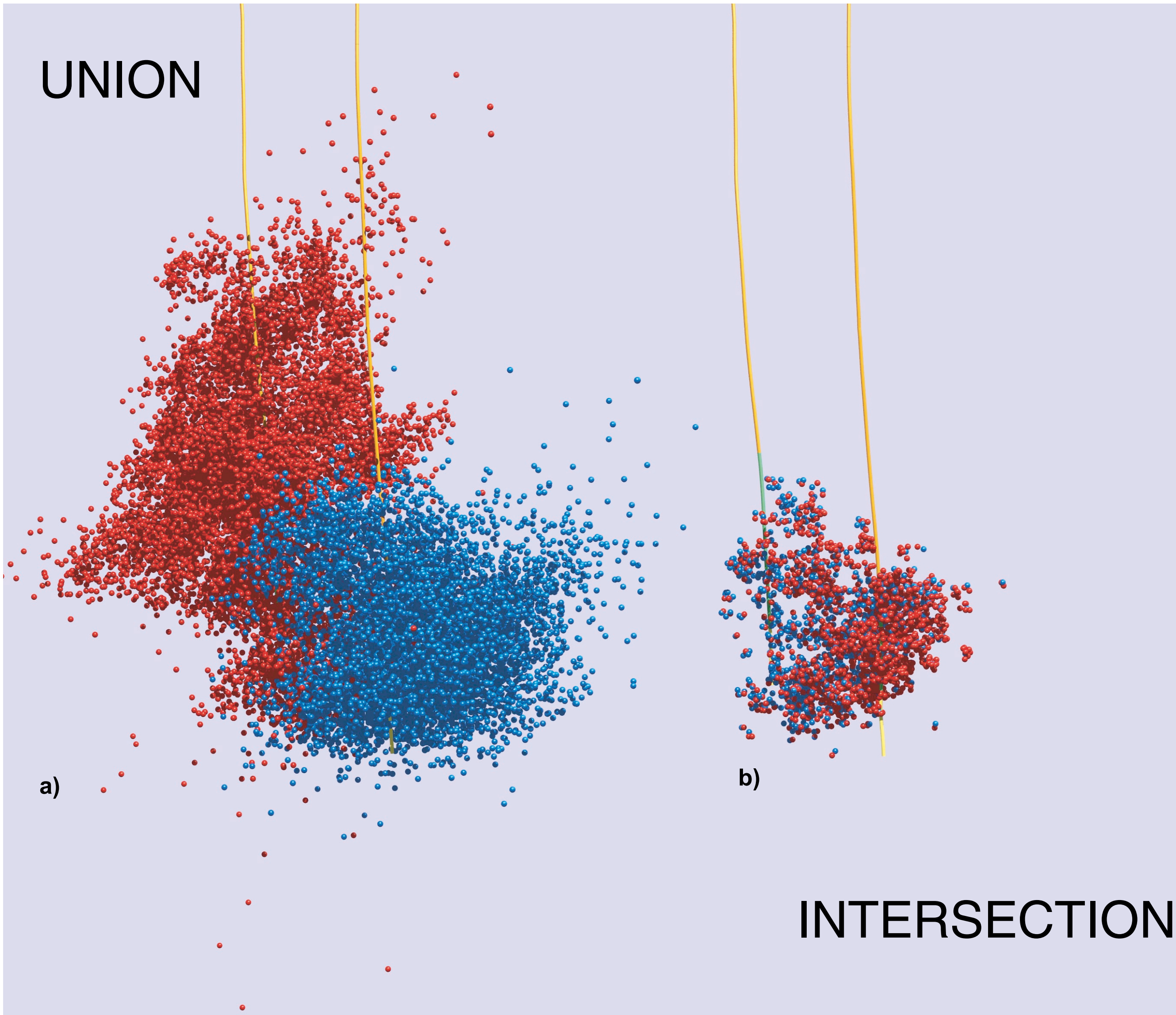


Figure 2. (a) Oblique view of locations of microearthquakes accompanying two stimulations into two nearby wells in Alsace, France. Locations of events accompanying each injection are shown in different colors. (b) Only seismicity that occupies the volume of rock that experienced critically elevated pressures during stimulation from each well (intersection) is shown.

are usually small, and observations in boreholes are required to provide waveforms having sufficient high-frequency content to determine reliable arrival-time information. Borehole observation sites are expensive so usually few are available. Therefore, the geometry of the recording array often does not provide data for the most reliable estimation of locations. Traditional earthquake seismology location techniques—such as single-event location determination and Joint Hypocenter Determination (JHD)—provide fuzzy images of microearthquake locations. The top section in Figure 1 shows map views of microearthquake locations within several depth intervals determined for a massive hydraulic stimulation conducted by the European Hot Dry Rock Geothermal R & D project in Alsace, France. Little structure can be seen. Using a method called collapsing, which was developed as part of the MTC project, the location pattern can be improved (Jones and Stewart, 1997; Fehler et al., 2000). Collapsing uses the existence of neighboring microearthquakes to obtain better locations of all microearthquakes. The collapsing method is based on the observation that a cluster of points occupies more volume when each point is perturbed by random errors than it does if no errors are present.

When a microearthquake is located using conventional methods, the confidence ellipsoid estimates where the event may be located within the uncertainty of the data. Conventional location procedures place the event location at the center of this confidence ellipsoid. Collapsing iteratively shifts each microearthquake location within its confidence ellipsoid toward the center of mass of events located within its confidence interval. The method can be viewed as a regularization constraint whereby information about the locations of nearby microearthquakes is used to improve its location. This regularization is similar to smoothing constraints used in tomographic imaging which cause the velocity of one node to be related to the velocity of neighboring nodes. Collapsing provides improved absolute locations but most importantly, it provides significantly improved relative locations of events. The lower set of maps in Figure 1 shows locations after the collapsing technique has been applied to the data in the upper set of maps. The structure of the zone of induced seismicity is more apparent in the postcollapsing set of depth slices. In this case, the collapsed data were successfully used to target a 3.5 km deep production borehole that was drilled through the zone of seismicity.

Figure 2a shows an oblique view of the locations of events accompanying two hydrofracturing operations conducted in two nearby wells at the European HDR site in Alsace, France. Prior to the stimulations, there was no hydraulic communication between the two wells so we may regard the data as consisting of two clouds of microseismicity. We conceptually consider these two clouds as distinct, geometric objects. From the viewpoint of constructive solid geometry, there are three ways in which objects may interact: union, difference, and intersection. The union of two objects is the object that encloses both original objects; this is what is typically shown when sets of microearthquake locations are plotted. The difference is an order dependent operator and results in an object that is the first object minus the second object. The intersection of the two objects is the volume that is occupied by both of the original objects, and is order independent. If we consider the regions within the seismic clouds induced by the individual stimulations as objects, we can form the union, difference, or intersection of these objects. The intersection of the two clouds from the two stimulations with microearthquake locations shown in Figure 2a is significant because it shows the volume of rock where the pore pressure was raised to at least that required for seismic activity in both stimulations. Hydraulic communication between the two wells accompanied the second stimulation. The intersection region (Figure 2b) is interpreted to be the zone where hydraulic communication is facilitated.

Relative locations were improved by signal processing methods—e.g., crosscorrelation to obtain more accurate relative arrival times and cross-spectral analysis to determine precise differences in hodograms of nearby events (see Tezuka and Niitsuma, 2000). Figure 3 shows results of applying cross-spectral analysis to data from a geothermal site in Japan. Locations obtained using a conventional technique are on the left and those obtained using cross-spectral analysis are on the right. Particularly noteworthy is that the zones of seismicity determined using the cross-spectral method intersect wells in regions where fluids enter the well (also shown in the figure). Another method that yielded extremely reliable results was simple manual picking of relative arrival times of events having waveforms that were similar in character (Phillips, 2000). Figure 4 shows an oblique view of the locations of a subset of events in Figure 1 that were determined using manual picks of relative arrival times. Note that the scale in the figure is significantly smaller than in Figure 1. The two nearly planar fractures can be seen to intersect and truncate one another.

Reflection methods: Seismic waveforms from active seismic sources are used extensively for seismic imaging. Members of the MTC project investigated the use of MS waveforms for imaging hydraulically stimulated reservoirs. One technique is to form a diffraction stack of MS waveforms to determine locations of strong scatterers within a reservoir (Soma et al., 1997). Prior to stacking, principal component analysis was applied to three-component seismograms in the wavelet domain to identify the waves arriving from the direction of an image point. Figure 5 shows an image obtained for a geothermal reservoir in Japan. The diffraction stack image shows strong reflections in regions where the accompanying geologic map indicates possible geologic discontinuities.

A diffraction stack scheme also was applied to three-component borehole recordings of waveforms generated by drilling to infer locations of scatterers (Asanuma et al., 2000). This method was applied to data from a region that also was

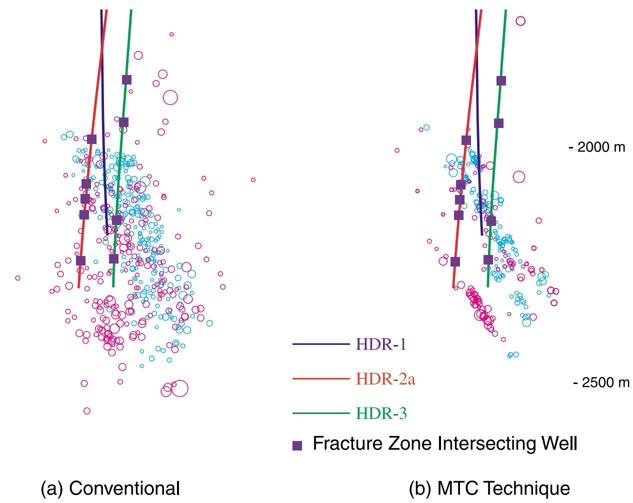


Figure 3. Locations of microearthquakes accompanying two hydraulic injections into two nearby wells at the Hijiori HDR reservoir in Japan. Locations of three wells are shown. The left plot shows locations determined using hodograms and traveltimes from one station and arrival times from a second station. The right plot shows locations determined using a doublet analysis method employing relative arrival times at the two stations, which provides improved relative locations of events. Black squares indicate zones where well logs indicate that flowing fractures intersect wells. Note that planes of seismicity intersect wells at locations of flowing fractures.

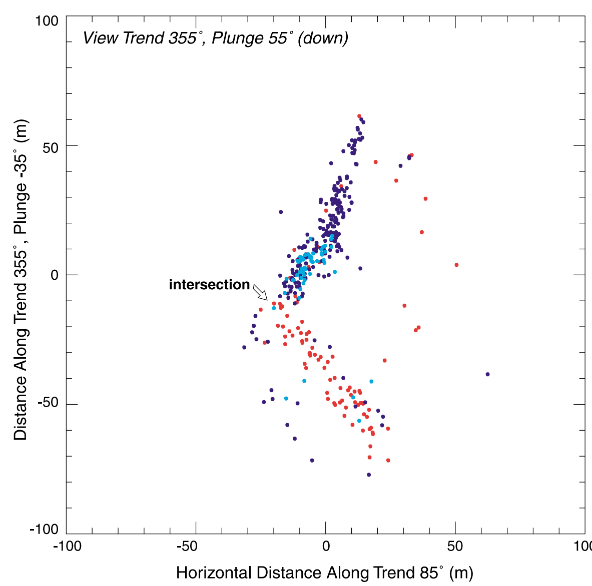


Figure 4. Oblique view of locations of microearthquakes that occurred during a hydraulic injection in Alsace, France. The events shown fall along two planar features that intersect along a common edge. The events within each plane all had similar waveforms so that reliable relative arrival times of *P*- and *S*-waves could be selected by hand.

investigated by diffraction stack of MS waveforms and similar results were obtained.

Hypocenter tomography: Hypocenter tomography has been used by earthquake seismologists to simultaneously infer locations of earthquakes and a 3-D velocity structure of the

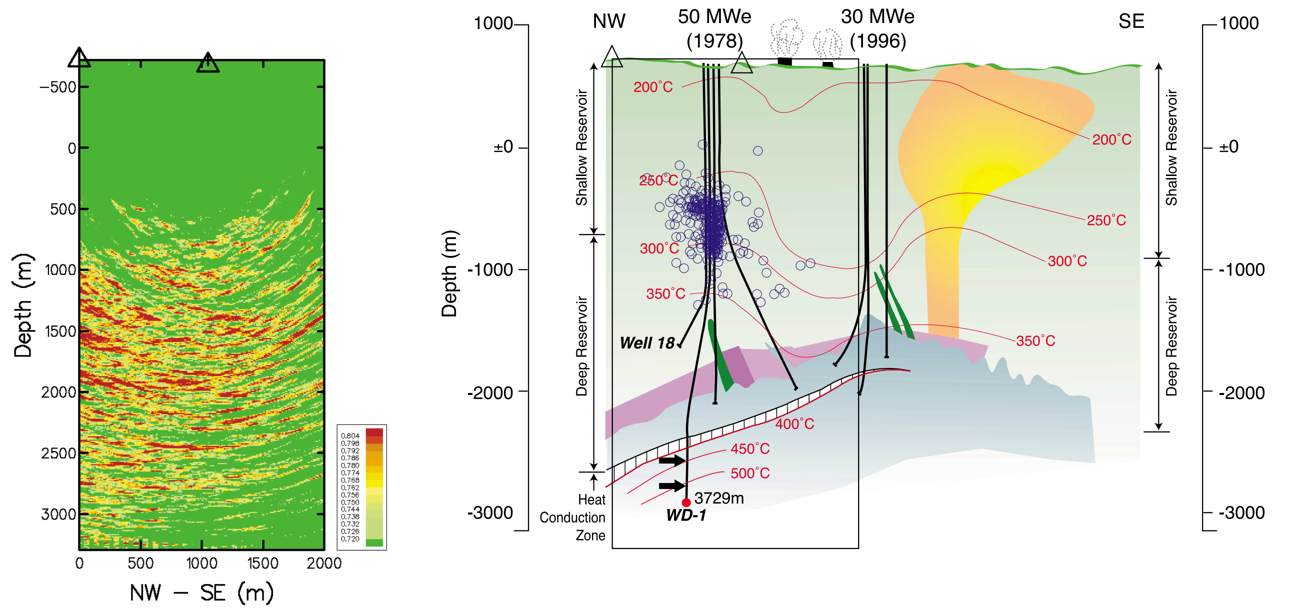
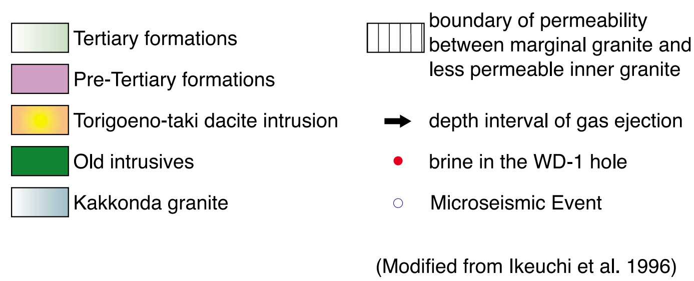


Figure 5. Reflection image of a producing geothermal field in Japan obtained by applying a principal component analysis in the wavelet domain to three-component seismograms and then constructing a diffraction stack. A geologic cross-section showing locations of microearthquakes is on right. The image shows strong reflections at locations where contrasts in geologic units occur.



region containing the earthquakes. The 3-D velocity structure correlates well with surface geology and locations of known subsurface features. We have investigated the application of hypocenter tomography to imaging the internal structure of a region containing MS events (Block et al., 1994). The difference between our investigations and conventional earthquake seismology is that we generally have fewer observation stations. However, we benefit because we have reliable arrival time picks for both *P* and *S* arrivals for the MS events. We find that seismic velocities decrease in stimulated zones and that some patterns in the associated 3-D velocity anomalies can be interpreted to infer locations of preferential fluid flow in the stimulated region.

Multicomponent signal processing: Signal processing approaches for improving the determination of *P*- and *S*-wave arrival times were investigated. Such approaches may ultimately be used for high-resolution estimation of arrival times without the interference of a human analyst and for real-time determination of event locations. Signal processing also was investigated for characterizing downhole multicomponent detectors. The goal is to quantitatively evaluate the in-situ transient response of the detector because the coupling of the detector with the borehole strongly influences the quality and reliability of the detected signal. We have found that the data redundancy provided by a tetrahedral four-component detector facilitates detailed analysis of the response of individual components of motion. This four-component detector allows more reliable measurements of ground motion and thus leads to better hodograms and cleaner waveforms for obtaining data for determining event locations.

A technique, known as the spectral matrix method, to characterize the ability of a borehole instrument to reliably record particle motion of incident waves (Niitsuma et al.,

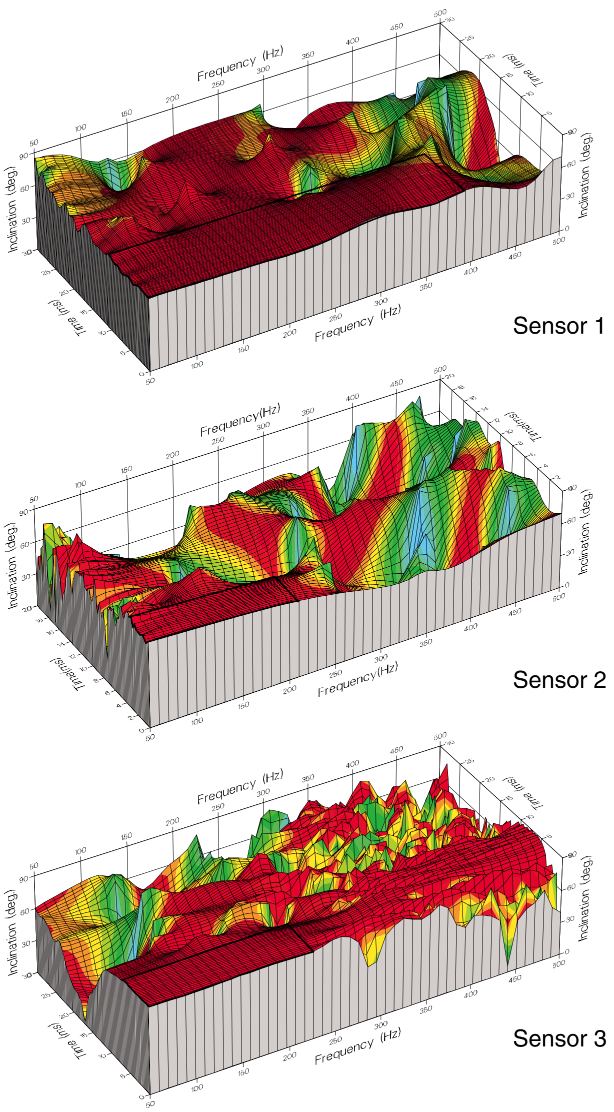


Figure 6. Evaluation of the polarization of hodograms from three borehole seismic sensors using the spectral matrix method. The frequencies over which the hodograms have the same polarization for a long time period, outlined by boxes, are the frequencies for which the seismic sensor is considered reliable. This method provides diagnostic information about reliability of specific deployments of a given sensor.

1995) is based on evaluation of the time-frequency character of the hodogram of a recorded waveform. Figure 6 shows the results of applying the spectral matrix method to three downhole detectors. The flat portions show the frequency range where the detectors are considered to provide reliable estimates of three-component ground motion.

Observations and modeling of crack waves: A theoretical analysis of waves guided by a fluid-filled crack led to a procedure for estimating hydraulic characteristics of the crack from field observations of waves that are guided along it. These guided waves are similar to Stoneley waves in boreholes. Successful field observations of guided waves led to estimation of the crack stiffness of a man-made fracture (Nagano and Niitsuma, 2000). The particle motion of the guided wave was used to infer the fracture orientation.

Conclusions. The MTC project facilitated development of a suite of new methods for understanding seismicity induced during hydraulic fracturing and reservoir production. These methods have application to geothermal reservoirs, petroleum reservoirs, mining-induced seismicity, and to characterization of rock formations being considered for disposal of waste. Improved measurements of the overall distribution and relative location of induced seismic events will allow construction and testing of models that include locations of potentially permeable fractures that are seismically active. Such models will help us make quantitative predictions about the relation between seismic events and reservoir flow paths which, in turn, will ultimately lead to better predictions of reservoir performance. These methods are now being applied to new regimes by MTC investigators and others in the field. A new project, called MURPHY (Multidisciplinary Understanding of Reservoir PHYsics), aims to combine analysis of seismic data with analysis of reservoir hydraulic data and knowledge of rock mechanics to provide a more comprehensive model of reservoir performance.

Suggested reading. "Discrimination of polarization of reflected waves in the triaxial drill-bit VSP and imaging of subsurface structure at Soultz, France" by Asanuma et al. (SEG 2000 *Expanded Abstracts*). "A method for determining significant structures in a cloud of earthquakes" by Jones and Stewart (*Journal of Geophysical Research*, 1995). "Calibration method using the spectral matrix for downhole triaxial seismic detectors" by Niitsuma et al. (*Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*, 1995). "Microseismic survey of a North Sea reservoir" by Dyer et al. (*World Oil*, 1999). "Current status of seismic and borehole measurements for HDR/HWR development" by Niitsuma et al. (*Geothermics*, 1999). "Precise microearthquake locations and fluid flow in the geothermal reservoir at Soultz sous-Forets, France" by Phillips (*Bulletin of the Seismological Society of America*, 2000). "Estimation of deeper structure at the Soultz Hot Dry Rock Field by means of reflection method using 3C AE as wave source" by Soma et al. (*PAGEOPH*, 1997). "Stress estimated using microseismic clusters and its relationship to the fracture system of the Hijiori hot dry rock reservoir" by Tezuka and Niitsuma (*Engineering Geology*, 2000). "A method for improving relative earthquake locations" by Fehler et al. (*Bulletin of the Seismological Society of America*, 2000). "Seismic imaging of the velocity structure in the vicinity of a hydrofrac in a geothermal reservoir" by Block et al. (GEOPHYSICS, 1994). "Dispersion analysis of crack waves in an artificial subsurface fracture using two crack models" by Nagano and Niitsuma (*IEEE Transactions on Geoscience and Remote Sensing*, 2000). LE

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